The Demographics of Extrasolar Planets Beyond the Snow Line with Ground-based Microlensing Surveys

White Paper for the Astro2010 PSF Science Frontier Panel

B. Scott Gaudi
The Ohio State University
gaudi@astronomy.ohio-state.edu
614-292-1914

J.P. Beaulieu[1], David P. Bennett[2], Ian A. Bond[3], Subo Dong[4], Andrew Gould[4], Cheongho Han[5], Byeong-Gon Park[6], Takahiro Sumi[8]

[1]Institute d'Astrophysique de Paris
[2]University of Notre Dame
[3]Massey University
[4]The Ohio State University
[5]Chungbuk National University
[6]Korea Astronomy and Space Science Institute
[7]Nagoya University

1. Overview

In the currently-favored paradigm of planet formation, the location of the snow line in the protoplanetary disk plays a crucial role (e.g. Ida & Lin 2004). Determining the demographics of planets with masses of the Earth or larger beyond the snow line of stars of various masses is thus essential for testing this model. In the inner parts of this region, RV probes the gas giants but not the ice giants nor, of course, terrestrial planets. RV cannot make reliable measurements in the outer part of this region at all because the periods are too long. Future astrometry missions (such as *SIM Lite*) could probe the inner regions down to terrestrial masses, but are also limited by their finite lifetime in the outer regions. Microlensing is sensitive to planets that are generally inaccessible to these other methods, and in particular is most sensitive to cool planets at or beyond the snow line, including very low-mass (i.e. terrestrial) planets. Hence, microlensing is uniquely suited and so essential for a comprehensive study of this region. Microlensing is also sensitive to planets orbiting low-mass stars, free-floating planets, planets in the Galactic bulge and disk, and even planets in external galaxies. These planets can also provide critical constraints on models of planet formation.

In its final report, the ExoPlanet Task Force (Lunine et al. 2008) recognized the major role microlensing has to play in determining the demographics of planets throughout the Galaxy, writing that "[t]he statistics of planetary masses and separations available from a microlensing survey are vital for constraining the theory of planet formation." They recommended that both ground and space-based microlensing be supported in the next 5-10 years. Here we focus on ground-based microlensing, and leave the discussion of space-based surveys for a separate paper (Bennett et al. 2009b).

We briefly review the properties of and current results from the microlensing method (see Bennett 2009a for a more thorough discussion), and then outline the potential of, and progress toward, next generation ground-based microlensing surveys. Detailed models of such surveys have already been carried out, and the required network of 1-2m class telescopes with wide FOV instruments is beginning to be constructed by several countries, including Japan, New Zealand, Poland, and South Korea. The US still has a substantial role to play in supporting these initiatives, through sharing of technical expertise in the design and construction of the telescopes, analysis of microlensing events from these surveys, contribution to follow-up observations, and potentially monetary and/or in kind contributions to supplement or augment the already-planned hardware investments.

2. The Properties of Microlensing Planet Searches

If a foreground star ("lens") becomes closely aligned with a more distant star ("source"), it bends the source light into two images. The resulting magnification is a monotonic function of the projected separation. For Galactic stars, the image sizes and separations are of order μas and mas respectively, so they are generally not resolved. Rather "microlensing events" are recognized from their time-variable magnification (Paczynski 1986), which typically occurs on timescales $t_{\rm E}$ of months, although it ranges from days to years in extreme cases. Presently about 900 microlensing events are discovered each year, almost all toward the Galactic bulge.

If one of these images passes close to a planetary companion of the lens star, it further perturbs the image and so changes the magnification. Because the range of gravitational action scales $\propto \sqrt{M}$, where M is the mass of the lens, the planetary perturbation typically

lasts $t_p \sim t_{\rm E}\sqrt{m_p/M}$, where m_p is the planet mass. That is, $t_p \sim 1\,$day for Jupiters and $t_p \sim 1.5\,$hours for Earths. Hence, planets are discovered by intensive, round-the-clock photometric monitoring of ongoing microlensing events (Mao & Paczynski 1991, Gould & Loeb 1992).

2.1 Sensitivity of Microlensing

While, in principle, microlensing can detect planets of any mass and separation, orbiting stars of any mass and distance from Earth, the characteristics of microlensing favor some regimes of parameter space.

• **Sensitivity to Low-mass Planets**: Compared to other techniques, microlensing is more sensitive to low-mass planets. This is because the *amplitude of the perturbation does not decline as the planet mass declines*, at least until mass goes below that of Mars (Bennett & Rhie 1996). The *duration* does decline as $\sqrt{m_p}$ (so higher cadence is required for small planets) and the probability of a perturbation also declines as $\sqrt{m_p}$ (so more stars must be monitored), but if a signal is detected, its magnitude is typically large ($\gtrsim 10\%$), and so easily characterized and unambiguous.

• **Sensitivity to Planets Beyond the Snow Line**: Because microlensing works by perturbing images, it is most sensitive to planets that lie at projected distances where the images are the largest. This so-called "lensing zone" lies within a factor of 1.6 of the Einstein ring radius, $r_{\rm E} = \sqrt{(4GM/c^2)D_s x(1-x)}$, where $x = D_l/D_s$ and D_l and D_s are the distances to the lens and source. At the Einstein ring, the equilibrium temperature is

$$T_{\rm E} = T_{\oplus}\left(\frac{L}{L_{\odot}}\right)^{1/4}\left(\frac{r_{\rm E}}{\rm AU}\right)^{-1/2} = 70\,{\rm K}\,\frac{M}{0.5\,M_{\odot}}[4x(1-x)]^{1/4}, \tag{1}$$

where we have adopted a simple model for lens luminosity $L \propto M^5$, and assumed $D_s = 8\,$kpc. Hence, microlensing is primarily sensitive to planets beyond the snow line.

• **Sensitivity to Free Floating Planets:** Because the microlensing effect arises directly from the planet mass, the existence of a host star is not required for detection. Thus, microlensing maintains significant sensitivity at arbitrarily large separations, and in particular is the only method that is sensitive to old, free-floating planets.

• **Sensitivity to Planets in the Disk and Bulge**: Microlensing searches require dense star fields and so are best carried out against the Galactic bulge, which is 8 kpc away. Given that the Einstein radius peaks at $x = 1/2$, it is most sensitive to planets that are 4 kpc away, but maintains considerable sensitivity provided the lens is at least 1 kpc from both the observer and the source. Hence, microlensing is about equally sensitive to planets in the bulge and disk of the Milky Way. However, future specialized searches may also be sensitive to closer planets and to planets in other galaxies, particularly the LMC and SMC, and M31.

• **Sensitivity to Planets Orbiting a Wide Range of Host Stars**: Microlensing is about equally sensitive to planets independent of host luminosity, i.e., planets of stars all along the main sequence, from G to M, as well as white dwarfs and brown dwarfs. By contrast, other techniques are generally challenged to detect planets around low-luminosity hosts.

• **Sensitivity to Multiple Planet Systems:** In general, the probability of detecting two planets (even if they are present) is the square of the probability of finding one, which means it is usually very small. However, for high-magnification events, the planet-detection probability is close to unity (Griest & Safizadeh 1998), and so its square is also near unity (Gaudi et al. 1998). In rare cases, microlensing can also detect exomoons (Bennett & Rhie 2002).

2.2 Planet and Host Star Characterization

It has often been stated that the ability of microlensing to provide detailed information about individual systems is very limited. This perception comes from the fact that (1) the host stars are typically distant and faint, making follow-up work is difficult, (2) in the overwhelming majority of microlensing events, the only parameter that can be constrained that contains any information about the primary lens is the event timescale $t_{\rm E}$, which is a degenerate combination of mass, distance, and transverse velocity of the lens, (3) microlensing detections routinely provide only the mass ratio of the planet and host star (Gaudi & Gould 1997), and so the mass of the planet is typically not known without a constraint on the primary mass, and furthermore (4) the only constraint on the planet orbit is $b_\perp$, the instantaneous angular separation between the planet and host star at the time of the event in units of the angular Einstein ring radius $\theta_{\rm E} = r_{\rm E}/D_l$. Since $\theta_{\rm E}$, the inclination, phase, and eccentricity of the orbit are all unknown, $b_\perp$ alone provides very little information about the orbit.

Experience has shown that, in reality, much more information can typically be gleaned from a combination of a detailed analysis of the light curve and high-resolution follow-up imaging. First, for the majority of planets detected via microlensing, the 'smoothing' effects of the finite source size are detectable during sharp features in the light curve caused by the planet. The magnitude of this effect yields $\theta_{\rm E}$. Second, for many long-duration events, it is also possible to measure the deviations in the microlensing light curve caused by the fact that the Earth is accelerating. This 'microlens parallax' allows one to constrain $\tilde{r}_{\rm E}$, the Einstein ring radius projected onto the observer plane. Third, for a substantial fraction of events, the lens light can be detected during and after the event (often in several different filters), allowing for a photometric estimates of the lens mass and distance, and so estimates of planet mass m_p and projected separation (Bennett et al. 2007). Finally, in some cases, the orbital motion of the planet during the microlensing event can be detected. Generally, if the lens mass is known, and under the assumption of a circular orbit, a measurement of the effects of orbital motion specify the full orbit of the planet (including inclination), up to a two-fold degeneracy (Dong et al. 2008a). In some cases, additional information can be used to break this degeneracy and strongly constrain the eccentricity of the orbit.

In many instances, several of these pieces of information can be measured in the same event, often providing complete or even redundant measurements of the mass, distance, and transverse velocity of the event. For example, a measurement of $\theta_{\rm E}$ from finite source effects, when combined with a measurement of $\tilde{r}_{\rm E}$ from microlens parallax, yields the lens mass $M = (c^2/4G)\tilde{r}_{\rm E}\theta_{\rm E}$, distance $d_l^{-1} = \theta_{\rm E}/\tilde{r}_{\rm E} + d_s^{-1}$, and transverse velocity.

For all eight published microlensing planet detections, it has been possible to measure $\theta_{\rm E}$ using finite source effects and so partially break the $t_{\rm E}$ degeneracy. For four systems (with five planets) it has been possible to uniquely measure the mass and distance to the planet and primary. Follow-up imaging with *HST* and/or ground-based adaptive optics would allow one to completely solve the remaining three events. In one exceptional case (Gaudi et al. 2008) redundant information on the primary mass and distance was obtained, and furthermore it was possible to constrain the eccentricity and inclination of the planetary orbit.

3. Present-Day Microlensing Searches

Microlensing searches today still basically carry out the approach advocated by (Gould &

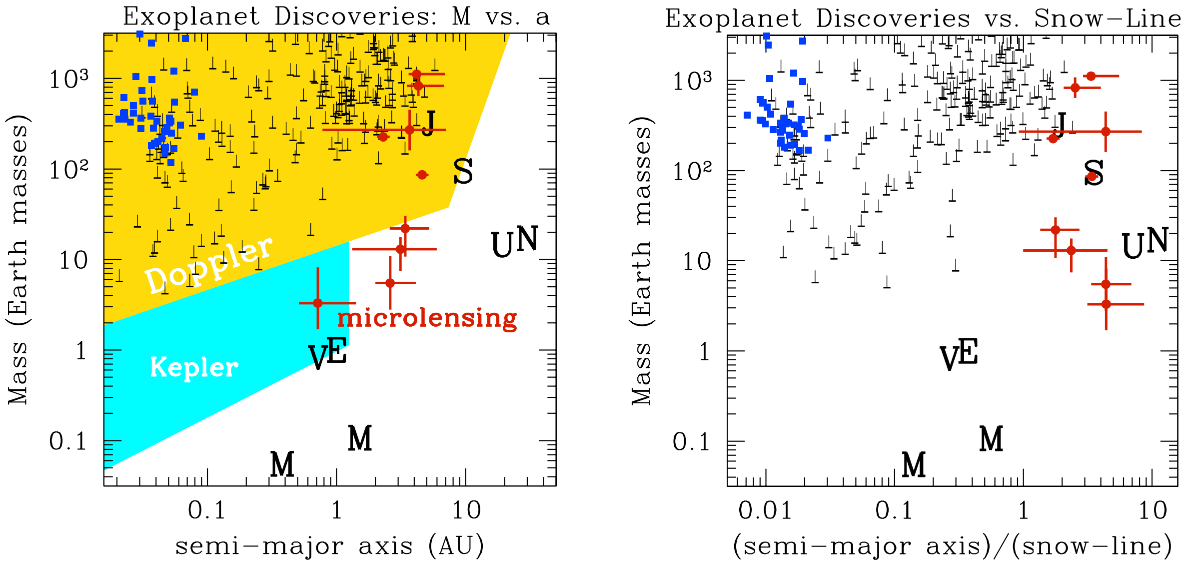

Fig. 1.— Distribution of known planets is plotted as functions of mass vs. semi-major axis (left) and semi-major axis normalized to the location of the snow-line (right). Planets found by the Doppler/RV method (black lines with error bars extending upward to indicate the $\sin i$ uncertainty), transits (blue squares), and microlensing (dark red error-bar crosses) are shown. The yellow shaded region indicates the expected sensitivity of the Doppler method assuming a 15 year survey with the present-day sensitivity. The cyan region indicates the expected sensitivity of the Kepler mission. Black letters show the locations of our Solar System's planets. The snow line is taken to be at $a_{\rm snow} = 2.7\,{\rm AU}\,M/M_\odot$.

Loeb 1992): International networks of astronomers intensively 'follow-up' ongoing microlensing events that are discovered and 'alerted' by two groups that search for events. Monitoring is done with 1m (and smaller) class telescopes. Indeed, because the most sensitive events are highly magnified, amateurs, with telescopes as small as 0.25m, play a major role.

To date, 8 planets have been published, and one will be submitted soon (See Fig 1). All are beyond the snow line with equilibrium temperatures $40\,{\rm K} < T < 70\,{\rm K}$. Two are members of a multi-planet system that resembles a solar system analog, suggesting that such systems are probably not rare (Gaudi et al. 2008). One is a low-mass planetary companion to a brown-dwarf star, which suggests that such objects can form planetary systems similar to those around solar-type main-sequence stars (Bennett et al. 2008). Three are Jupiter class planets and so are similar to the planets found by RV at these temperatures (Bond et al. 2004; Udalski et al. 2005; Dong et al. 2008b). One of these is the most massive planet ($\sim 3\ M_{\rm Jup}$) yet found around an M-dwarf (Dong et al. 2008a), whose existence may pose a challenge for the core-accretion theory of planet formation. Four are 'super-Earth' planets, with $3M_\oplus \lesssim M \lesssim 20M_\oplus$, which are substantially lighter than planets detected by RV at these temperatures (Beaulieu et al. 2006; Gould et al. 2006; Bennett et al. 2008; Sumi et al. 2009). These low-mass planet detections imply that $\sim 20\%$ of stars have $\sim 10\ M_\oplus$ planets with separations of $\sim 1.5 - 4$ AU.

4. Next Generation Microlensing Searches

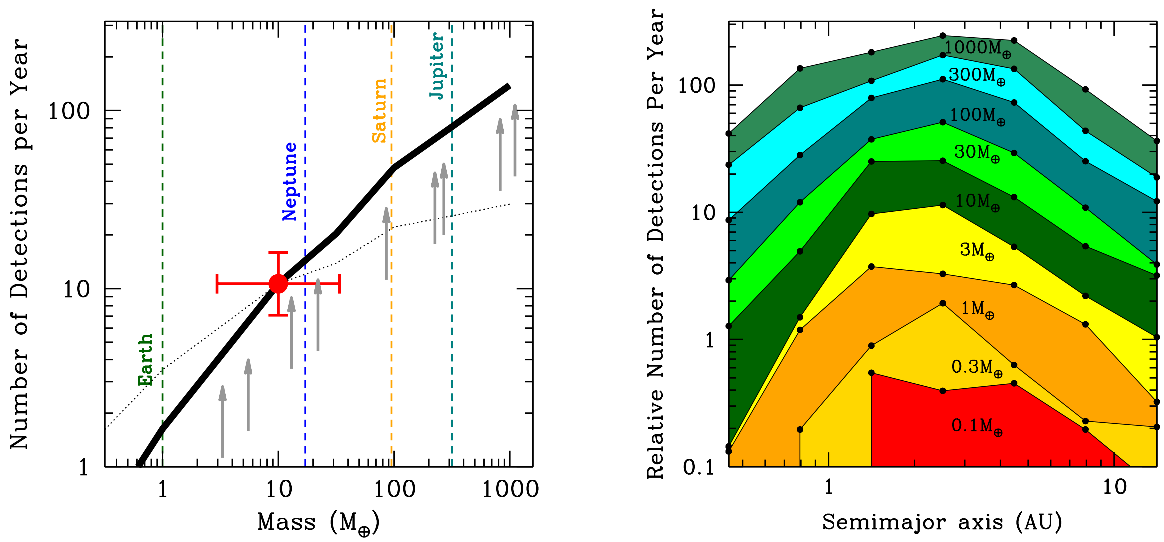

Fig. 2.— Expectations from the next generation microlensing survey, including MOA-II, OGLE-IV, and a Korean telescope in South Africa. (Left) Number of planets detected per year, normalized to number of $\sim 10 M_\oplus$ found to date by microlensing (indicated by the red dot). The solid line is the prediction assuming an equal number of planets per logarithmic mass interval, and the dotted grey curve assumes that the number of planets per log mass scales as $m^{-1/3}$. Planets are assumed to be distributed uniformly in $\log(a)$ between 0.4-20 AU. Arrows indicate the locations of 8 published exoplanets plus one unpublished planet (Sumi et al. 2009). (Right) The semi-major axis distribution of the detected planets.

While the early successes of the microlensing method are encouraging, it is widely recognized that the rate of microlensing detections cannot easily be increased beyond a few per year without a change in strategy. Next-generation microlensing experiments will operate on completely different principles from the current two-tier, 'alert/follow-up' model. Instead, wide-field ($\sim 4\,\mathrm{deg}^2$) cameras on 1-2m telescopes on 3–4 continents will monitor large ($\sim 10\,\mathrm{deg}^2$) areas of the bulge once every 10 minutes around-the-clock. The higher cadence will more than double the number of events per year, from $\sim$ 900 to several thousand. More important: *all of these events will automatically be monitored for planetary perturbations by the search survey itself,* as opposed to roughly 50 events monitored per year as at present.

Detailed simulations of such a wide-FOV telescope network have been performed by two independent groups (Bennett 2004; Gaudi, Gould, & Han, unpublished), both represented on this white paper. These simulations assume 3 wide FOV, 1-2m telescopes located in Chile, Australia, and South Africa. Normalizing by the number of super-Earth ($\sim 10 M_\oplus$) planets found to date, and assuming a frequency of planets that is constant per log mass interval, these simulations predict that this network will detect $\sim$ 1.6 Earths and 10 super-Earths per year (see Fig. 2). In particular, the Earth-mass planet detection rate will be higher than the current $\sim$ 1 super-Earth per year detection rate. Finally, a next generation survey would detect hundreds of Jupiter-mass free-floating planets per year if every star has ejected a Jupiter-mass planet.

In fact, the microlensing community is close to acquiring the hardware needed for such a

next-generation survey. The current microlensing survey groups, MOA and OGLE, have already made significant progress in this direction. MOA is currently operating the 1.8m MOA-II telescope with a 2.2 $\deg^2$ FOV, and OGLE is in the midst of upgrading the camera on its 1.3m telescope to the 1.4 $\deg^2$ for the OGLE-IV survey, which should commence in 2009. MOA also plans to upgrade to a 10 $\deg^2$ camera within a few years. Finally, the South Korean congress has recently approved the Korean Microlensing Telescope Network (KMTNet) project, which will consist of three 1.6m-class telescopes with $\sim 4\,\deg^2$ CCD cameras, to be built in South Africa, Chile, and Australia over the next 5 years.

4.1 US Role in Next Generation Surveys

While it appears that the major telescope hardware investments for the next generation planetary microlensing survey will be made almost exclusively by other countries, including Japan, New Zealand, Poland, and South Korea, there are a number of avenues by which US can still play a significant role in the future of ground-based microlensing planet searches. It is essential that we take advantage of these opportunities, as it is clear that this field is increasingly being dominated by other countries, and we are in danger of losing our current competitive edge when the next generation of students is trained on next-generation experiments in other countries.

Consider, for example, the KMTNet Project: this is an enormous undertaking, which will likely benefit greatly from international participation. Sharing of technical expertise and experience between Korean and US scientists and engineers with instrumentation expertise will likely be beneficial for the timely and efficient design and construction of the three facilities. Furthermore, given the rather uncertain economic climate, completion of this ambitious project may ultimately prove too costly for any single government. If the US can share some of the financial burden through monetary and/or in-kind contribution, this would ensure the project's success.

Second, it may be advisable to augment the already-planned facilities with additional telescopes. For example, simulations indicate that the addition of a fourth facility in Hawaii would increase the detection rate by $\sim 20\%$, and would improve the characterization of some poorly-sampled planetary perturbations. It may be possible to use already-existing hardware for this purpose; for example the Pan-STARRS PS1 telescope (Kaiser 2004) perfectly fulfills the requirements for such a facility.

Third, US scientists will likely have an important role to play in the development of modeling software to analyze the events found in these surveys. There are currently only a handful of people in the world that have the expertise required to model planetary microlensing events, and a significant fraction of them are in the US.

Finally, there will be a substantial role for follow-up observations in next-gen microlensing surveys. These follow-up observations will come in many varieties. First, high-precision photometry of planetary deviations alerted real-time will improve coverage and significance of the deviations. Second, next-gen surveys will also dramatically improve prediction of high-mag events prior to peak, which would improve planet detection by triggering more frequent observations during peak planet detection sensitivity. Just as with current microlensing planet searches, many of these observations could be carried out by small telescopes, such as those of the Las Cumbres Observatory Global Telescope (Brown et al. 2006), and those be-

longing to amateur astronomers around the globe. Third, it will be necessary to characterize the host stars using high resolution photometry with space-based or ground-based adaptive optics facilities, such as is currently available with VLT and Keck, and will be available with future facilities such as JWST or future large telescopes such as TMT and GMT.

6. Conclusion and Outlook

Although microlensing searches have so far detected only a handful of planets, these have *already* changed our understanding of planet formation in the critical region beyond the snow line. Next generation microlensing surveys, which would be sensitive to tens of "cold Earths" in this region, are well advanced in design conception and are starting initial practical implementation. These surveys play an additional crucial role as proving grounds for a space-based microlensing survey, the results of which are likely to revolutionize our understanding of planets over a broad range of masses, separations, and host star masses (Bennett et al. 2009b).

Although the major telescope hardware investments for the next generation planetary microlensing survey will be made almost exclusively by other countries, the US can still play a significant role, through sharing of technical expertise, analysis of events from these surveys, follow-up observations, and potentially monetary and/or in kind contributions to supplement or augment the already-planned hardware investments.

References

Beaulieu, J.-P., et al. 2006, Nature, 439, 437
Bennett, D. P. 2004, ASP Conference Proceedings, 321, 59 (astro-ph/0404075)
Bennett, D. P., & Rhie, S. H. 1996, ApJ, 472, 660
Bennett, D. P., & Rhie, S. H. 2002, ApJ, 574, 985
Bennett, D. P., Anderson, J., Bond, I. A., Udalski, A., & Gould, A. 2006, ApJL, 647, L171
Bennett, D. P., Anderson, J., & Gaudi, B. S. 2007, ApJ, 660, 781
Bennett, D. P., et al. 2008, ApJ, 684, 663
Bennett, D. P. 2009a, in Exoplanets: Detection, Formation, Properties, Habitability (arXiv:0902.1761)
Bennett, D. P., et al. 2009b, White Paper for the Astro2010 PSF Science Frontier Panel
Bond, I. A., et al. 2004, ApJ, 606, L155
Brown, T. M., et al. 2006, BAAS, 208, 5605
Dong, S., et al. 2008a, ApJ, in press (arXiv:0804.1354)
Dong, S., et al. 2008b, ApJ, submitted (arXiv:0809.2997)
Gaudi, B. S., & Gould, A. 1997, ApJ, 486, 85
Gaudi, B. S., Naber, R. M., & Sackett, P. D. 1998, ApJ, 502, L33
Gaudi, B. S., et al. 2008, Science, 319, 927
Gould, A., & Loeb, A. 1992, ApJ, 396, 104
Gould, A., et al. 2006, ApJ, 644, L37
Griest, K., & Safizadeh, N. 1998, ApJ, 500, 37
Ida, S., & Lin, D. N. C. 2004, ApJ, 604, 388
Kaiser, N. 2004, SPIE, 5489, 11
Lunine, J. I., et al. 2008, Final Exoplanet Task Force Report (arXiv:0808.2754)
Mao, S., & Paczynski, B. 1991, ApJ, 374, L37
Paczynski, B. 1986, ApJ, 304, 1
Sumi, T., et al. 2009, in preparation
Udalski, A., et al. 2005, ApJ, 628, L109